Power electronics for very high power applications

The insulated gate bipolar transistor (IGBT) and integrated gate commutated thyristor (IGCT) will be the power electronics components of choice for FACTS and other high-power applications in emerging markets in the next decade. New developments in semiconductors and in their packaging technology will drive power electronics increasingly into distribution applications, with device efficiency and reliability increasing as the cost of the switched megawatt falls.

The last 50 years have seen power conversion grow to a point where today about 15 % of the electrical power produced is converted electronically in one form or the other. Most of this conversion, however, still occurs at the 'consumer end' of the supply chain. Similarly, although HVDC transmission has exploited line-commutated power electronics for the past three decades, it has taken until the 1990s for self-commutated power electronics to become established at the transmission level. At the threshold of the 21st century, industry and society at large are facing a new era in which distribution applications for power electronics will continue to become more commercially viable – the result of new developments in semiconductors and their packaging technology driving up device efficiency and reliability as the cost of the switched megawatt falls.

Power electronics applications

Industry and traction

Power electronics devices typically have been employed in areas in which their benefits are most cost-effective. Early applications were in power supplies, battery chargers and motor drives. The 1960s saw the introduction of line-commutated control (thyristor and diodes) in traction applications, followed in the 1970s by fast thyristors and diodes in self-commutated applications (choppers and inverters). The 1980s witnessed a rapid expansion of industrial motor drives thanks to the development of the Darlington and Triplington bipolar power transistors as well as the GTO (Gate Turn-off Thyristor) and IGBT (Insulated Gate Bipolar Transistor).

During the early 1980s the transistor-based structures pushed the thyristor-based structures (fast thyristors and GTOs) towards higher powers, and by the early 1990s GTOs had become 'very high power devices' suitable for traction and high-power (> 1 MW) or medium-voltage (> 2.3 kV) industrial drives. IGBTs, with their simple drive requirements (voltage control), displaced Darlington transistors (current control) as the component of choice for low-voltage drives up to 480 Vrms, and by the mid-1990s had also displaced GTOs in LV drives up to 690 Vrms due to the widespread availability of devices rated to 1800 V.

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This low-cost availability has turned the LV drives industry into a US$ 3 billion market with a growth rate of about 7% per annum.

The emergence of the IGCT (Integrated Gate-Commutated Thyristor) [1] in the late 1990s has given a new impetus to the drives industry by doing to medium-voltage drives up to 6900 Vrms [2] what IGBTs did for LV drives up to 690 Vrms. This market represents US$ 0.5 billion, with a growth rate of about 15 % pa on account of the large number of MV motors in the field. 95 % of these motors operate without torque and speed control due to the absence, until now, of cost-effective drive solutions at these voltage levels.

Generation, transmission and distribution

Over the last 30 years the driving forces behind power electronics lay in the cost-effective implementation of control at the user level either to stabilize voltages (power supplies) or to control motor speed, acceleration and torque (industrial processes and transportation). The transmission and distribution industry also has its problems to solve, but has traditionally not had cost-effective solutions for them. Notable exceptions have been high-voltage DC (HVDC) for transmitting DC power over long distances at up to 1 MV and static var compensators (SVCs) for controlling inductors or capacitors for voltage stabilization. All of these have relied on phase control thyristors (PCTs) to control power, primarily because they offer the highest power control and hence the most cost-effective, if not necessarily the best, solutions. The generation industry has had little call for power electronics at the output stage since the powers are typically very high (250 MW) and generators operate in synchronism with the infinite grid.

Emerging markets

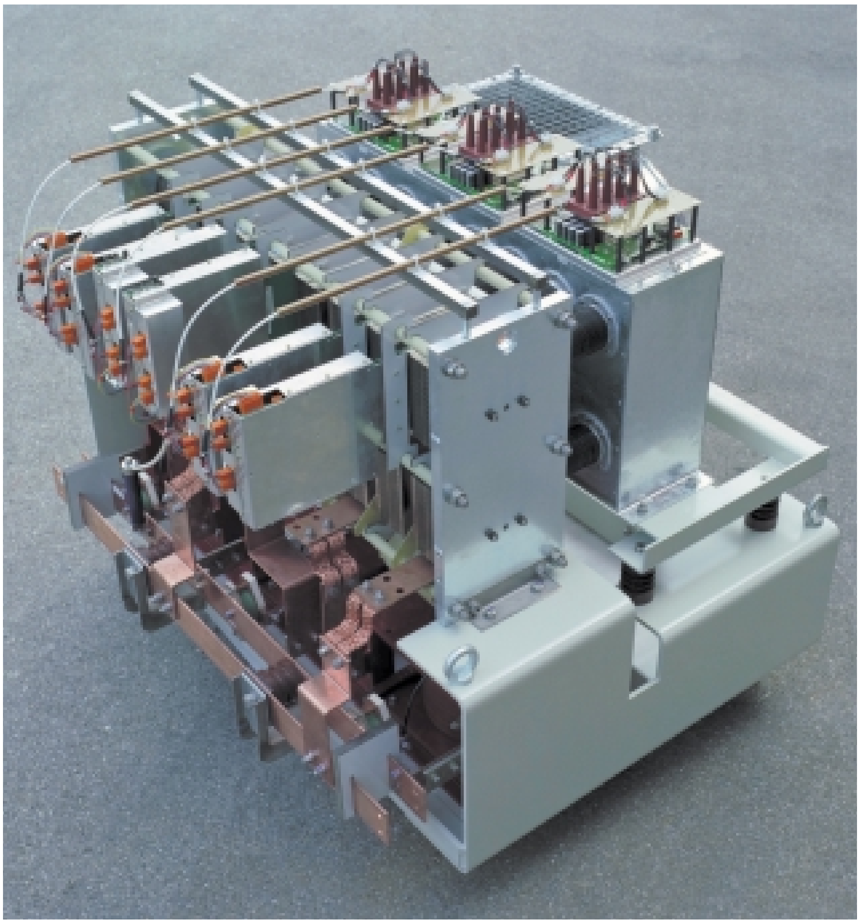
New applications are emerging (*Table 1*) that lie between the worlds of traction and industry and those of generation, transmission and distribution. These applications are loosely grouped under the headings 'FACTS' (Flexible AC Transmission Systems), 'power quality' and 'custom power' **1**. The forces driving these trends are the deregulation of power utilities worldwide, the growth of production processes requiring unperturbed sources of electric power (eg, plastic foil or semiconductor manufacturing), and environmental issues.The latter emphasize the importance of efficient transmission and consumption of electricity but also make it more difficult, for example, to install additonal transmission lines.

These non-traditional power electronics applications have been variously estimated to represent a world equipment market of up to US$ 3 billion in the early years of the next century and have therefore the potential to match the importance of the traditional traction and industrial drives markets.

Components

The choice of semiconductor devices for the emerging markets seems limited for the coming years (*Table 2*). Though many device structures are repeatedly presented and discussed, most remain either in the domain of low power or in the research field. The only devices under serious consideration for the present and the foreseeable future are the IGBT, the GTO and the IGCT, whereby the GTO is destined to be replaced by the IGCT since it offers no advantages over the latter.

This in effect leaves only two contenders for high-power applications, and in any discussions of their relative merits the often forgotten but crucial fast recovery diode must be considered as it plays a deciding role in whether a thyristor



Three-phase, IGCT-based converter rated at 1.5 MW and 1 kHz, from ABB Industrie AG. The converter is for a dynamic voltage restorer. **1**

Equivalent circuit of a thyristor **2**

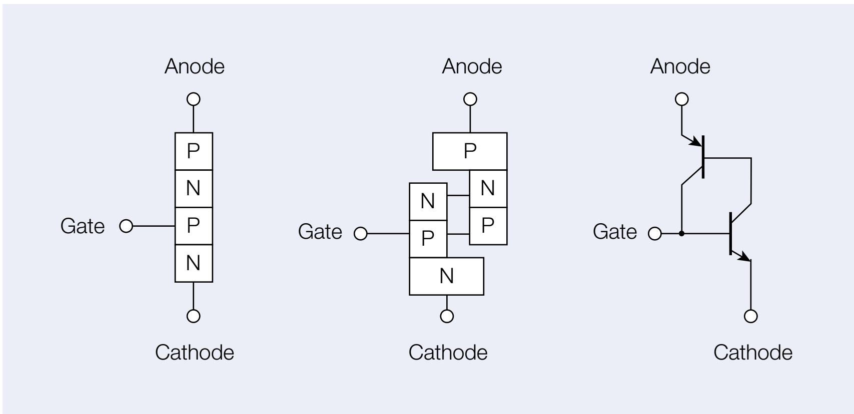


Table 1:
Emerging applications for power electronics

Application	*Description*	*MW (typical)*	*Segment*
STATCOM	*Static compensator* Allows both leading or lagging power factors to be corrected seamlessly with a minimum of installed capacitance, allowing voltage stabilization and load balancing	100	T&D, industry, traction
UPFC	*Unified Power Flow Controller* Converter-based system which controls power flow, voltage and power factor, allowing optimal, stable use of existing lines	200	T&D
DVR	*Dynamic Voltage Restorer* Instantly reacts to drop in line voltage (sub-cycle) and restores missing portion of waveform from an energy storage device (eg, battery)	2–100	Power quality
Transfer switch	Transfers load to alternative lines	5–30	Power quality
Static breaker	Interrupts faults with sub-cycle response	5–30	Power quality, traction
Intertie	Allows energy exchange between asynchronous three-phase and/or single-phase systems	2–300	Utilities, traction, industry
VAR-Speed	AC excitation of synchronous motor-generators for speed control	30	Generation
Local generation	Fuel cells (dc output) or small turbo-generators running at high or variable speeds requiring output frequency conversion	2	Generation
Energy storage/ UPS	Short-term (< 1 hr) energy storage and restitution ('peak-load shaving) with batteries, fly-wheels, superconducting magnetic energy storage (SMES), etc	1–100	Power quality, T&D, traction, industry
Active filter	Compensates harmonic distortions in MV networks	1–30	Power quality
Short DC link	Short distance HVDC (100 kV) transmission links from utility to load and from alternative power sources to grid	50	T&D

or a transistor should be the self-commutated element.

Semiconductor packaging is also an important parameter for determining the appropriate technology for a given topology. Although all present power semiconductors are based on silicon, and as such all packaging options are equally available to IGBTs, IGCTs and diodes, the structure of the device conditions its preferred encapsulation, which in turn influences the circuit layout.

Device selection criteria

Although the semiconductor device may represent only 1 % of the cost of a large installation, such as a 100-MW intertie, its influence on the performance and on the capital and running costs of the final system is disproportionately large. Equipment design criteria are the same for all applications, but the weight that each one carries depends on the application. The equipment parameters are, in the order of their general ranking:

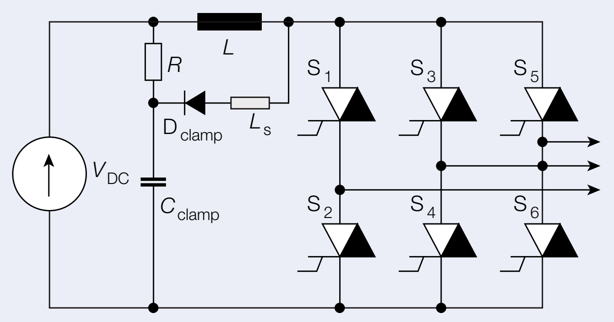
- Cost of the device and circuit
- Reliability (wear, random failures)
- Efficiency at full and part load
- Size (weight, volume, footprint)

These *system* requirements translate into the following *device* requirements:

- Low device costs
- Rugged operation (few ancillary components)
- High reliability (low random failures, high power and temperature cycling, high blocking stability)
- Simple assembly and repair (modularity)
- High currents (turn-off, rms, average, peak, surge)
- High voltages (peak repetitive, surge, dc-continuous)
- Fast switching (short on/off delays, short rise/fall times, short turn-on/off times)
- Low losses (conduction, switching)
- High frequency (fast switching, low switching losses)

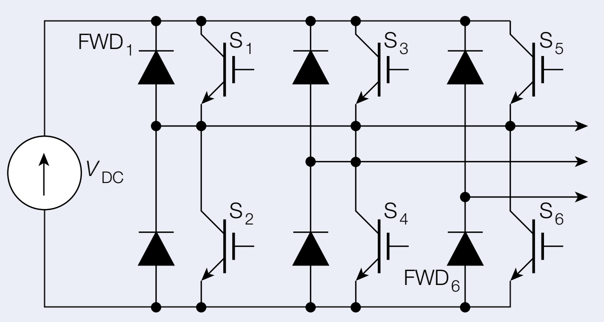
Thyristors and transistors

As seen in *Table 2*, self-commutated devices fall into one of two categories: thyristors or transistors, each with very distinctive differences which translate into real and perceived advantages and disadvantages as the above listed goals are sought. It is not coincidental that the two



Typical IGCT inverter **3**
(patent pending)

C_{clamp} *Clamp capacitor*
D_{clamp} *Clamp diode*
L *Inductance*
L_s *Stray inductance of clamp circuit*
R *Resistance*
S_{1-6} *Switches 1–6*



Typical IGBT inverter **4**

FWD_{1-6} *Freewheeling diodes 1–6*
S_{1-6} *Switches 1–6*

practical contenders for high power belong to these two categories.

Transistors are *amplifiers* which allow large collector currents to be varied by a small controlling base current, as in conventional bipolar transistors, or, in the case of the more sophisticated IGBTs, by a gate voltage requiring very little current and hence little control power. The gate control circuit can vary the speed at which switching on or off occurs.

Thyristors are *switches* composed of a regenerative pair of transistors **2**. Once the regenerative action is initiated (or interrupted) the thyristor switches very rapidly from 'on' to 'off', and vice versa, with the gate unit exercising little, if any, control of the speed at which this occurs.

Any adjustment of the speeds at which the anode voltage and current change during switching (d*i*/d*t* and d*v*/d*t*) must be performed by external components or be designed into the intrinsic behaviour of the device. In the case of the IGCT this is easily achieved for turn-off d*v*/d*t* through the anode design, but not so easily for d*i*/d*t* at turn-on, which results in the basic circuits shown in **3** and **4**, respectively, for IGCT and IGBT 3-phase, 2-level inverters. As many of the emerging high-power applications in *Table 1* will be based on self-commutated voltage-source inverters, the discussions of these two key components will relate to this simple inverter topology.

3 shows a typical IGCT inverter with a d*i*/d*t* limiting circuit inserted between the quasi zero-impedance supply (dc link) and the inverter. Inductance *L* limits the rate-of-rise of current in the inverter when one of the IGCTs (switches S1 to S6) is turned on. The limitation of current rise is deter-

Table 2:
Available self-commutated semiconductor devices

Thyristors	*Transistors*
• GTO (Gate Turn-Off Thyristor)	• Bipolar transistor
• MCT (MOS Controlled Thyristor)	• Darlington transistor
• FCTh (Field Controlled Thyristor)	• MOSFET
• SITh (Static Induction Thyristor)	• FCT (Field Controlled Transistor)
• MTO (MOS Turn-Off Thyristor)	• SIT (Static Induction Transistor)
• EST (Emitter Switched Thyristor)	• IEGT (Injection Enhanced (insulated) Gate Transistor)
• IGTT (Insulated Gate Turn-Off Thyristor)	• **IGBT** (Insulated Gate Bipolar Transistor)
• IGT (Insulated Gate Thyristor)	
• **IGCT** (Integrated Gate-Commutated Thyristor)	

Open GCT (a) showing reverse-conducting silicon wafer (top center) and complete IGCT (b) rated 4.5 kV/2.6 kA **5**

mined by the allowable rate-of-fall of current in the associated diodes, which in most IGCTs is integrated on the same wafer 5. The energy stored in inductance *L*, once the diode is commutated, is subsequently dissipated in resistance *R*; the optional clamp capacitor, C_{clamp}, can be used to minimize voltage overshoot.

In the event of failure of two devices in one phase, the resulting current, I_{fault}, is limited by the inductance to a value given by:

$$I_{fault} = V_{DC} \cdot \sqrt{C/L} \tag{1}$$

where *C* is the capacitance of the DC link. 4 shows an IGBT inverter consisting solely of semiconductor components; it can be realized in a single module for low-power systems, but is generally composed of multiple modules comprising IGBT and diode chips connected in parallel to achieve the desired rating 6.

The advantage of the module topology shown in 6 lies in the complete absence of ancillary components, the d*i*/d*t* controlling function being implemented by gate control, whereby turn-on of the IGBT is slowed to match the allowable turn-off speed of the diode. It can be shown [3] that the resulting losses generated in the IGBT are the same as those dissipated in the resistance of 3. In 4 the absence of impedance (eg, an inductance) between the power electronics (inverter) and the DC link results in extremely high fault currents in the event of simultaneous failure of two devices in the same phase. This fact limits the direct applicability of the topology in 4 to low voltages (up to about 1.5 kV) or small DC link capacitors. At higher voltages and powers, decoupling of the link and inverter via inductance or resistance is required to limit co-lateral explosion damage caused by vaporization of the chip bond wires and the electromagnetic forces of the fault current [4].

An exception to this may be found in very high voltage systems involving a large number of series-connected IGBTs in which there may be a number of redundant devices. Here, if the proper service intervals are respected, nothing short of a direct lightning strike would cause simultaneous failure of all redundant devices in a phase leg, making the omission of link impedance once again feasible. 7 shows an IGBT 'presspack module' specially designed for series connection [4]. Here, the parallel-connected IGBT and diode chips are pressure-contacted, each contact being designed to take the full-load current should a chip fail. Series operation of the stack is thus assured (with appropriate redundancy) if one component fails short.

Diodes

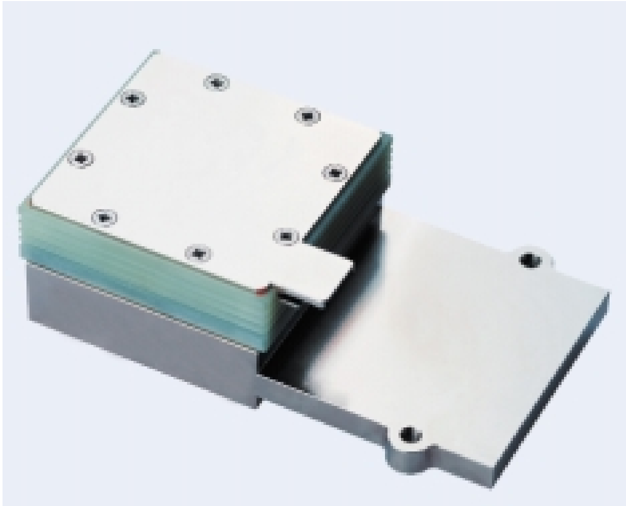
As indicated above, the diode plays a determining role in the topology chosen, since it dictates the allowable turn-on d*i*/d*t* of a voltage-source inverter and hence determines the principal part of the turn-on losses that will be dissipated in the silicon 4 or in the resistance 3. The relevant waveforms are shown in 8.

It has been shown [3] that the circuit-specific turn-on losses, $E_{on-circuit}$, are given approximately by:

$$E_{on-circuit} = \frac{V_{DC}^{2} \cdot I_{peak}^{2}}{2 \cdot k \cdot P_{rrmax}} \tag{2}$$

where *k* is a constant and P_{rrmax} is the maximum diode reverse recovery power for safe operation. The higher the P_{rrmax} of the diode (also a measure of its safe operating area, SOA) the lower the

IGBT module rated 2500 V/1200 A (single switch) **6**



IGBT presspack module rated 2500 V/700 A, for series connection **7**

circuit-specific turn-on loss (it can be shown that minimum circuit-specific losses occur when the reverse recovery peak, I_{RR}, is roughly equal to the load current [4]).

8 shows the voltage collapse over the device generating a subsequent device-specific loss, $E_{on-device}$, given by:

$$E_{on-device} \approx I_{peak} \cdot \int_{t3}^{t2} V_{switch}(t) \cdot dt \qquad (3)$$

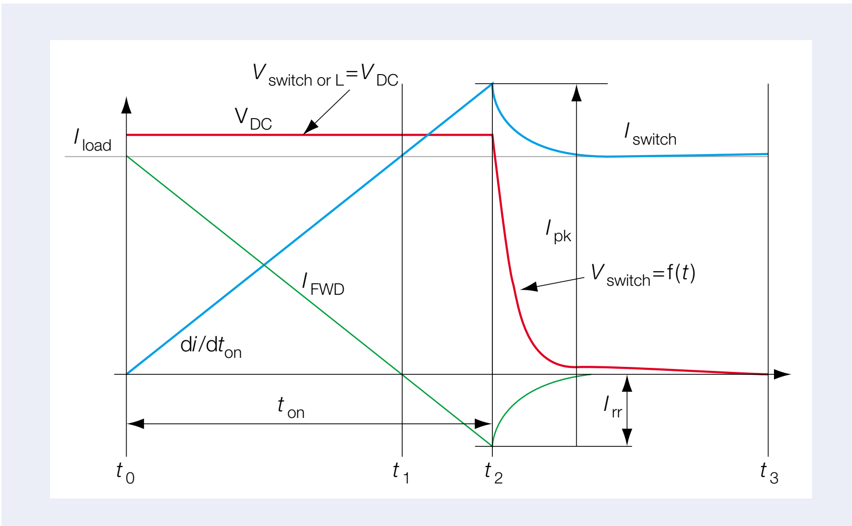
in which V_{switch} is the voltage across the device as it falls to its steady on-state value. Exploiting an increased diode SOA as per equation (2) will reduce $E_{on-circuit}$, but increase $E_{on-device}$ so that in the absence of a d*i*/d*t* limiting choke the IGBT turn-on losses can only be reduced by increasing the diode speed, whereas if a choke is used both an increase in speed and SOA will reduce losses and ensure that they are not dissipated in the silicon of the active switch. Present silicon diodes are reaching their performance limits and will probably reach their SOA limits by the end of this century. Thus, the turn-on loss limitations of chokeless topologies will not change until the arrival of silicon carbide diodes allowing 100 times lower switching losses [5]. Though laboratory samples exist at voltages up to 5 kV, reliable, cost-effective components are not likely to become common until the latter half of the next decade.

Cost, reliability, frequency and efficiency

Cost, reliability, frequency and efficiency will be important factors in future trans-

General turn-on waveforms for Figs 3 and 4 **8**

I_{FWD}	*Freewheel diode current*
I_{load}	*Load current*
I_{pk}	*Peak current*
I_{switch}	*Steady-state switch current*
di/dt_{on}	*Rate-of-rise of switch current*
V_{DC}	*DC supply voltage*
$V_{switch\ or\ L}$	*Voltage across switch or inductor*
t_0	*Instant of switch turn-on*
t_{on}	*Duration of current rise*
t_1	*Instant switch current reaches steady-state load current*
t_2	*Instant diode current reaches peak value*
t_3	*Instant switch voltage falls to steady-state value*



mission applications. The first two are compatible as they are derived from a minimal component-count. Frequency, however, as required by active filtering, is at odds with all the goals because switching losses increase with frequency and reduce the useful power a component can handle, thus increasing the component-count and reducing reliability. In the very high power applications given in *Table 1*, IGCTs allow instantaneous switching powers of 16 MW today, but will nevertheless require series or parallel connection to fulfil the requirements of those applications. Since they are generally for medium to high voltages (10 kV and above), primary consideration will have to be given to series connection [6].

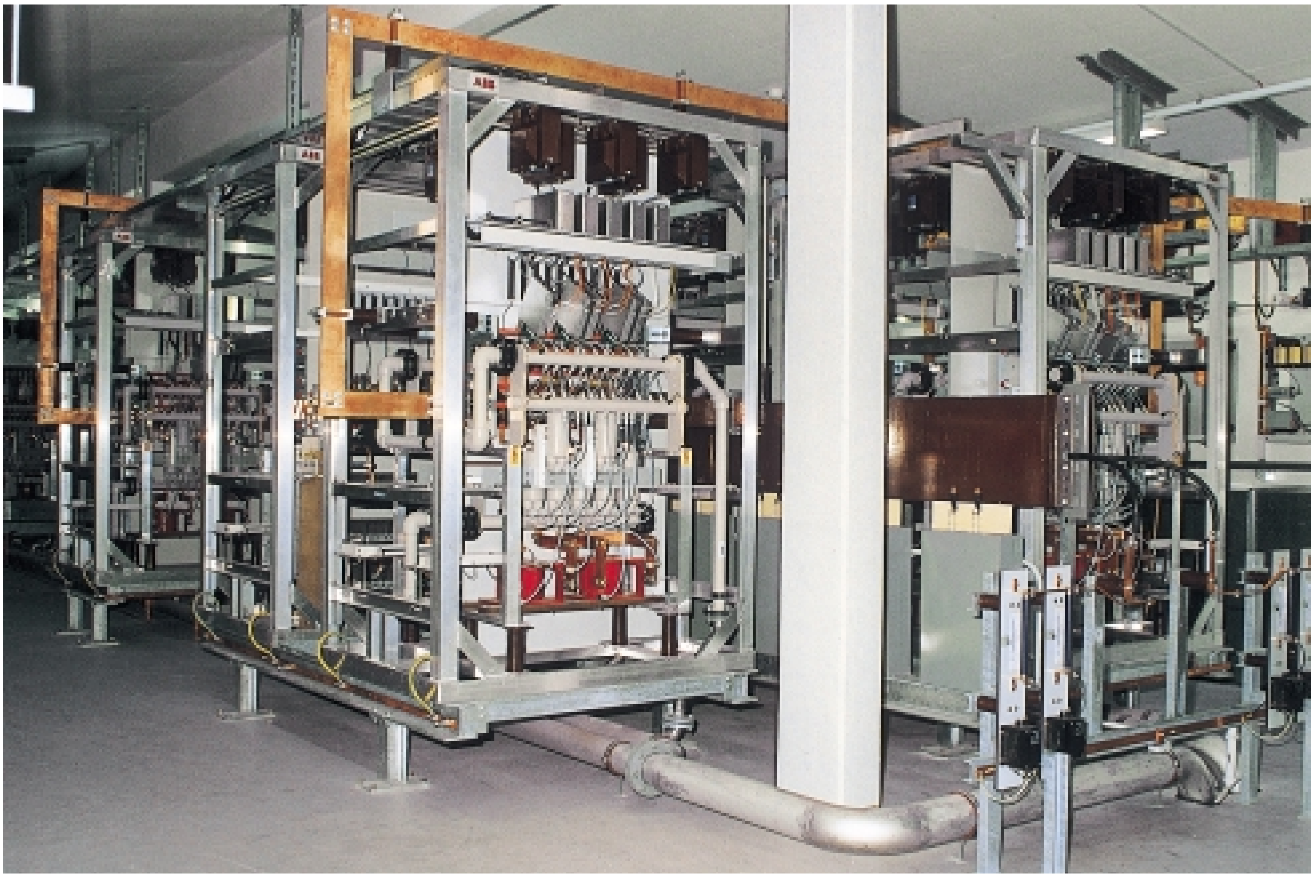
Inverters rated at 100 MW have already been realized using first-generation IGCTs in direct series connection [7], albeit at line frequency. Today, 5-MW IGCT inverters operating directly on the 4,160-V MV line, without snubbers or series connection, are entering commercial service at 500–1000 Hz pulse-width modulation. Second-generation IGCTs with losses 30 % lower than those of only 3 years ago are now being designed into STATCOMs and such interties as the 100-MW installation at Karlsfeld, Germany [11] **9**. These devices now have the snubberless turn-off ratings (4 kA) of conventional GTOs fitted with 6 μF snubbers.

IGBTs and IGCTs both fulfil the requirements of 'rugged switching', which implies the ability to turn off without commutation networks or 'd*v*/d*t* snubbers'. These networks are 'undesirable' not only because of the added costs and losses they engender but also because they impose time constants which in turn limit operating frequency. Because of their low losses and snubberless operation 6-kV IGCTs can operate at 500 Hz, with burst operation up to 25 kHz at full rating [8]. Higher frequencies – determined by thermal limits – are possible with lower voltage devices, namely 1 kHz for 4.5 kV and 3 kHz for 3.3 kV devices.

Equipment volume or, more frequently the footprint, are also cost drivers in any major installation. It is believed that IGCT inverters hold the record for compact construction, with values of 13 to 20 kVA per liter having been reported along with efficiencies of 99.65% at 200 Hz pwm [1].

IGCTs and IGBTs are both transistors when turning *off*, and as such they generate the same losses. The turn-on losses have already been discussed and are negligible for IGCTs with their obligatory d*i*/d*t*

100-MW, 16-Hz traction converter at Karlsfeld, Germany, scheduled for commissioning in October, 1999 **9**



controlling chokes; hence, the 'external' circuit-specific losses (which are recoverable at the cost of additional circuitry) are not considered in the thermal budget of the device. In the conducting state the IGCT is a *thyristor* with two injecting emitters giving it half the conduction loss of a transistor structure and allowing more room in the thermal budget for dynamic losses, and hence for frequency.

The GTO, the traditional workhorse of power electronics, has exhibited a constant component cost per MVA reduction of 20 % pa over the last decade. The GCT has arrested this trend but has halved driver costs, reduced cooling costs by 30 % and eliminated snubber and even freewheel diode costs, resulting in over 30 % cost reductions in power electronics in a single step.

Trends and improvements

Currently, IGBTs and IGCTs are commercially available up to 3.3 and 6 kV, respectively. These voltages can be increased to 6.5 and 9 kV, respectively, by the end of the century providing the increased losses of such devices can be tolerated in their prospective applications. Current 4.5-kV IGCTs on 4-inch wafers are rated up to 4 kA, but the potential for reaching 6 kA at 6 kV has been demonstrated [4].

Inorganic passivants, such as diamond-like carbon, will allow higher DC voltage ratings or operating junction temperatures, and new materials, such as the metal matrix aluminium silicon carbide, may reduce thermal resistance by allowing wafer bonding to the package. IGBT modules with built-in water-cooling are already being developed for traction applications and the principle could be applied to monolithic IGCTs.

Conventional phase control thyristors will continue to dominate traditional HVDC [9] and the newly introduced bi-directionally controlled thyristor (BCT) will become an important component in conventional var compensation [10].

Conclusions

IGBTs and IGCTs will be the principal component players in the multitude of FACTS applications emerging over the next decade. In very high current and medium voltage applications, the thyristor structure will be the favoured approach, especially where decoupling chokes are deemed desirable or mandatory.

The IGBT in the chokeless configuration **4** will greatly benefit from the rapid progress being made in silicon carbide diodes, although commercial arrival of the latter on the FACTS scene is not imminent. Nevertheless, the IGBT will continue to be favoured in the lower-cost chokeless topology wherever this adequately offsets the higher cost of the component itself.

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